

Analysis of Stop Quarks with Small Stop-Neutralino Mass Difference at a Linear Collider

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Introduction

- An Extension of scalar top studies for small visible energy in the detector.
- Theoretical motivation: The origin and stabilization of electroweak symmetry in particle physics and the nature of dark matter and baryogenesis in cosmology both suggest the existence of new symmetries within the reach of the next generation of colliders.
- Recently, the universe dark matter energy density has been precisely measured by the Wilkinson Microwave Anisotropy Probe (WMAP) to be $\Omega_{\text{CDM}} h^2 = 0.1126 \pm 0.0161 \text{ (stat)} \pm 0.0181 \text{ (sys)}$.
- The super-symmetry with R parity conservation provides a stable neutral dark matter candidate, the Neutralino with mass and $\sigma \sim e.W$ energy scale.
The Neutralino-Stop co-annihilation region is characterized by a small mass difference $M(\text{stop-neutralino}) = 20\text{-}30 \text{ GeV}$, with relic density compatible with the WMAP observation. The stop decays into neutralino and charm is the only decay channel allowed.
- Possible benchmark for vertex detectors and material budget.

Theoretical Motivation

- Electroweak Baryogenesis:

Sakharov Requirements:

- 1- Baryon Number Violation - (SM - Anomalous process)
- 2- C & CP violation - (SM-Quark CKM mixing)
- 3- Departure from Equilibrium - (SM-At EW phase transition)

Limitations of SM:

2)Not Enough CP violation & 3) $\rightarrow M_{Higgs} < 40 \text{ GeV}$, LEP Bound $M_{Higgs} > 114.4 \text{ GeV}$

\rightarrow Supersymmetry with light scalar top, below the top mass: $m_{\tilde{t}_1} < m_t$

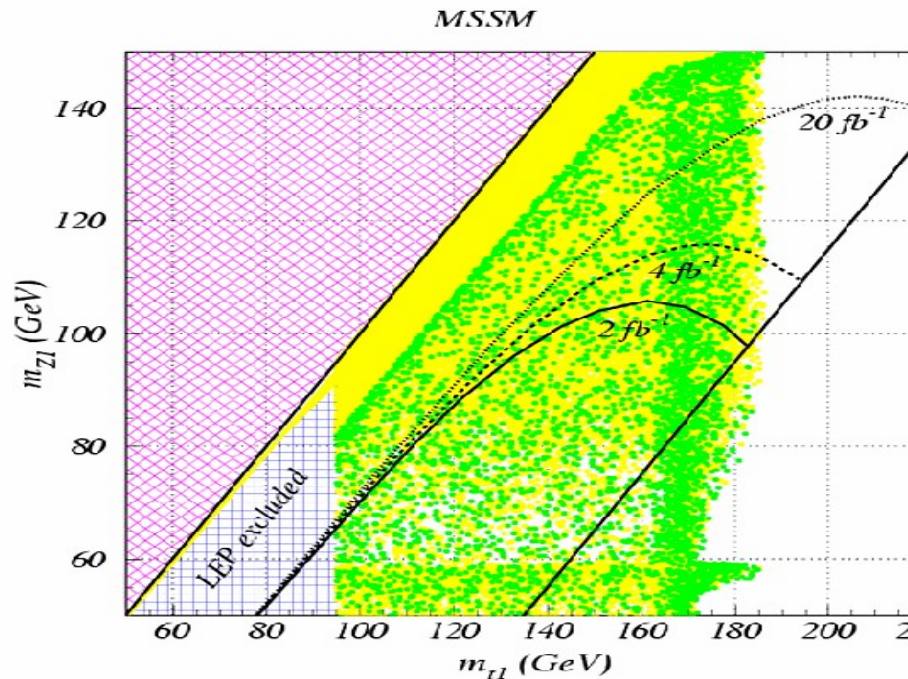
- Dark Matter

The Supersymmetric Lightest particle (LSP), the neutralino X^0_1 is a candidate

The annihilation cross-section $\sigma_a (X^0_1, X^0_1)$ too small

But for $m_{\tilde{t}_1} - m_{X^0_1} \sim 20\text{-}30 \text{ GeV}$, there is co-annihilation between the \tilde{t}_1 and the $X^0_1 \rightarrow \sigma_a (X^0_1, \tilde{t}_1) + \sigma_a (X^0_1, X^0_1)$ consistent with dark matter.

Dark Matter: A Case For The ILC



- On the figure* is represented a random scan of the parameter space projected on the plane, stop mass versus neutralino mass.
- In green is the region with a relic density consistent with the WMAP observations over- layed the Tevatron light stop search sensitivity in the charm decay channel.
- The co-annihilation region for $\Delta m \leq 30$ GeV is out of reach due to background reduction limitations inherent to hadron colliders.
- This region is the region under study with the linear collider.

*C. Balazs, M. Carena, CEM Wagner-hep-ph/0403224-v2-aug 04

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Selection $e^+e^- \rightarrow \tilde{t}_1 \bar{\tilde{t}}_1 \rightarrow c\tilde{\chi}_0^1 \bar{c}\tilde{\chi}_0^1$

- Pythia with Simdet/Tesla was used for the simulations of both signal and background with CIRCE for the beamstrahlung.
- Signature: 2 soft charm jets + missing energy
- Luminosity = 500 Fb^{-1} ; $\sqrt{s} = 500 \text{ GeV}$

• A short list of the sequential cuts applied as a preselection first, allowed larger samples to be produced and the cut refined at selection stage.

Pre-selection:

- $4 < \text{Number of Charged tracks} < 50$
- $P_t > 5 \text{ GeV}$
- $\cos\theta_{\text{Thrust}} < 0.8$
- $|P_{l,\text{tot}}|/P < 0.9$
- $E_{\text{vis}} < 380 \text{ GeV}$
- $M(\text{inv}) < 200 \text{ GeV}$

Selection:

- $N_{\text{jets}} = 2$
- $\cos(\Phi_{\text{A-coplanarity}}) > -0.9$
- $\cos\theta_{\text{Thrust}} < 0.7$, $P_t > 12$ revisited.
- $E_{\text{vis}} < 0.4 \sqrt{s}$
- $3500 \text{ GeV}^2 < \text{Minv}_{\text{jets}}^2 < 8000 \text{ GeV}^2$
- c-tagging- From T. Khul

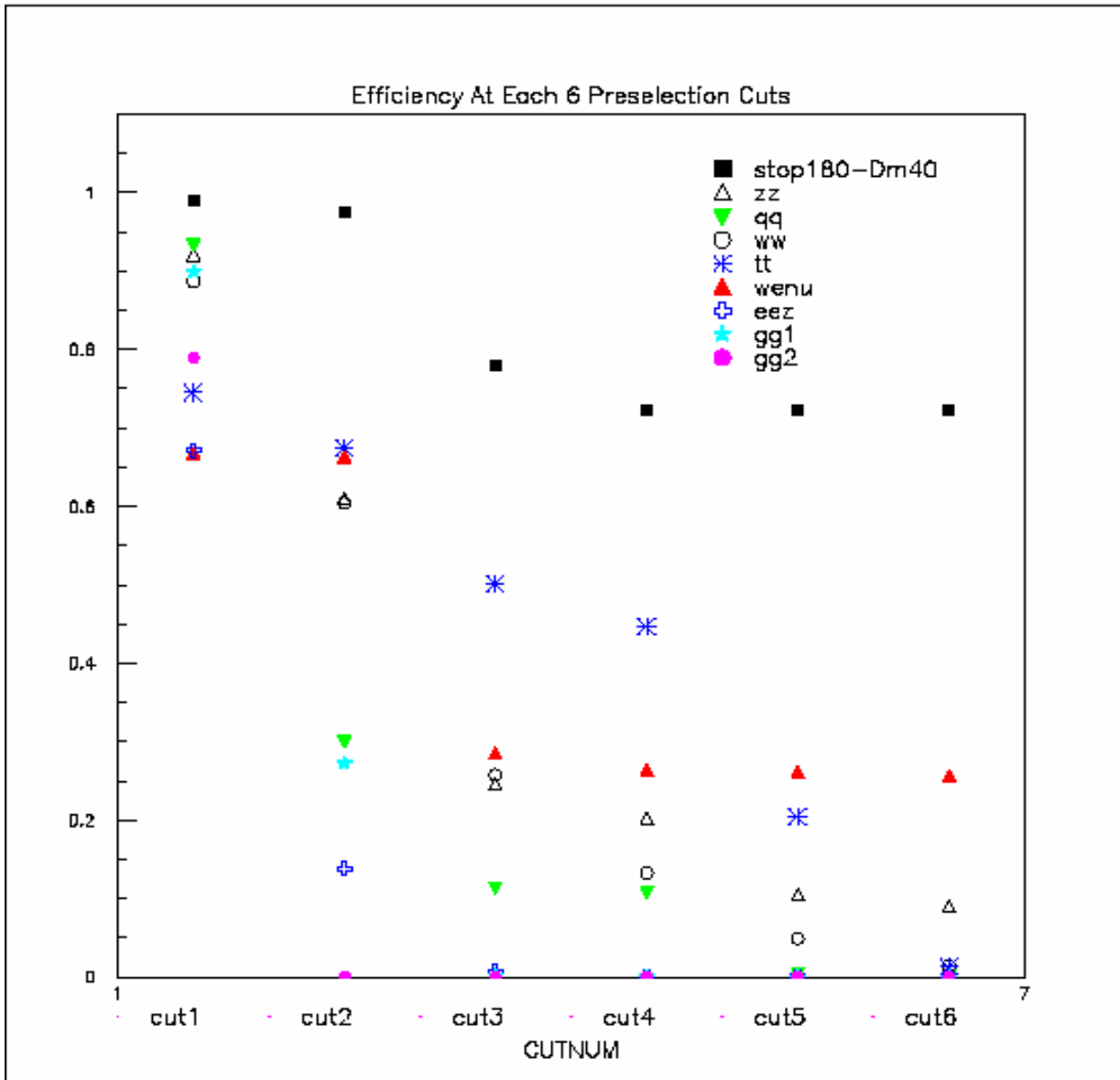
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Signal And Background Cross-Sections (pb)

Process	$\sigma(\text{pb})$ - A. Freitas		
	Pr(0,0)	Pr(-80,+60)	Pr(+80,-60)
$\tilde{t} \tilde{t}^* - M_{\tilde{t}_1}=120 \text{ GeV}$	0.280	0.374	0.456
$M_{\tilde{t}_1}=140 \text{ GeV}$	0.217	0.289	0.353
$M_{\tilde{t}_1}=180 \text{ GeV}$	0.105	0.140	0.171
$M_{\tilde{t}_1}=220 \text{ GeV}$	0.025	0.033	0.040
w^+w^- - Pythia 7.38	8.55	24.54	0.77
$w\text{ev}$ - 5.30	6.14	10.57	1.82
ZZ - 0.402	0.49	1.02	0.44
eeZ - 6.90	7.51	8.49	6.23
$t\bar{t}$	0.55	1.13	0.50
$qq, q \neq t$	13.14	25.35	14.85
$\gamma\gamma, p_T > 5 \text{ GeV}$ 936.			

Pr(-80,+60)= P(e-)/P(e+)= -80%/+60% ; Pr(+80,-60)= P(e-)/P(e+)= +80%/-60%
 $\sigma(eez)$ & $\sigma(W\text{ev})$ are from Grace and do not include Beamstrahlung/ISR

Pre-selection: Efficiency Each Cut



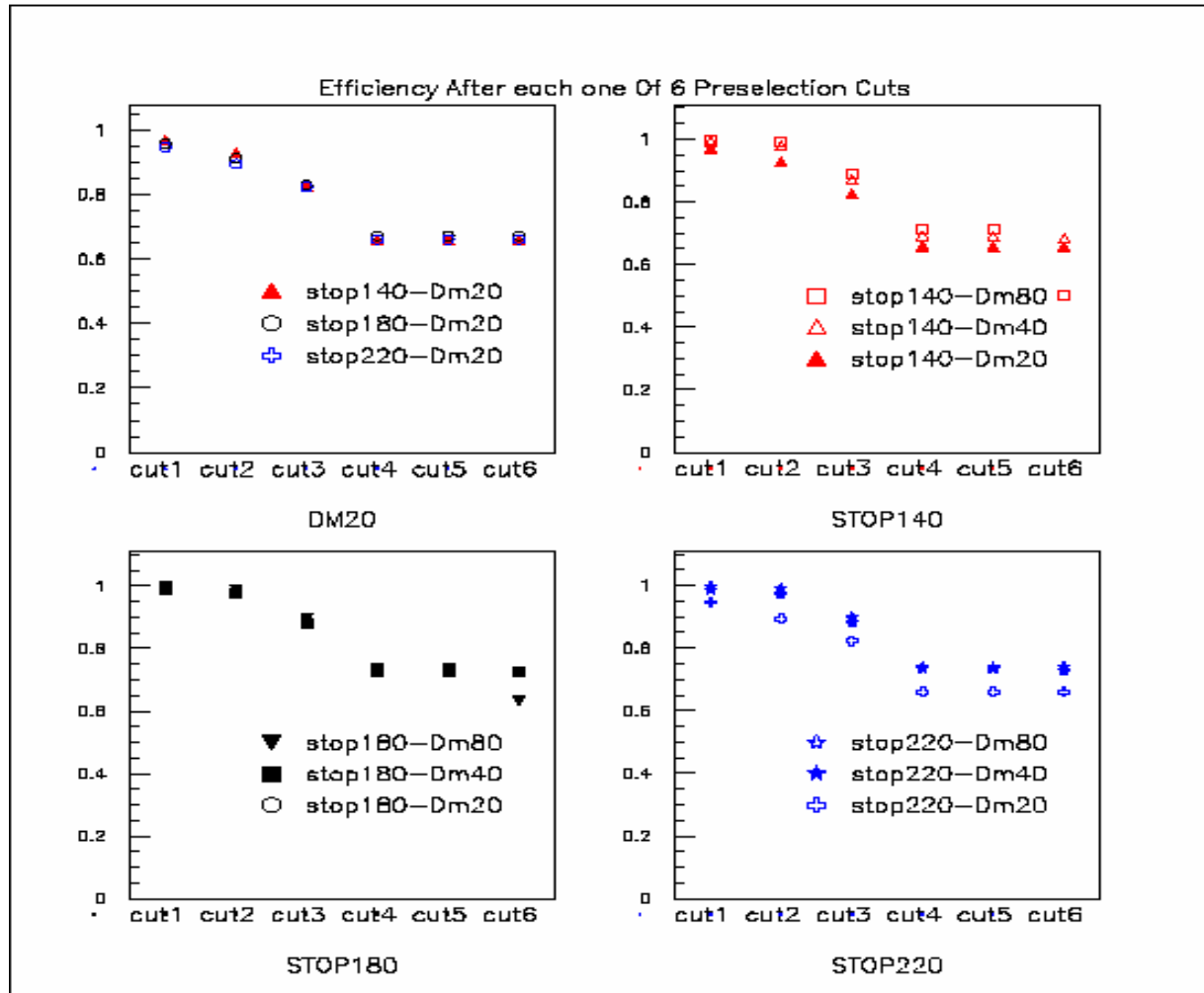
Colour point:

% of Background
left after each cut,
Reduced < 30%

Black Points:

% of signal left after
each cut for
~70% signal left

Pre-selection Efficiency: Stop



Upper Left:

$\Delta M(\tilde{t}_1 - X_0) = 20 \text{ GeV}$

$\tilde{M}_{\tilde{t}_1} = 140 \text{ GeV}$

$\tilde{M}_{\tilde{t}_1} = 180 \text{ GeV}$

$\tilde{M}_{\tilde{t}_1} = 220 \text{ GeV}$

Independent of $\tilde{M}_{\tilde{t}_1}$

Others:

$\Delta M(\tilde{t}_1 - X_0) =$

20, 40, 80 GeV

Separately for $\neq \tilde{M}_{\tilde{t}_1}$

~Independent of

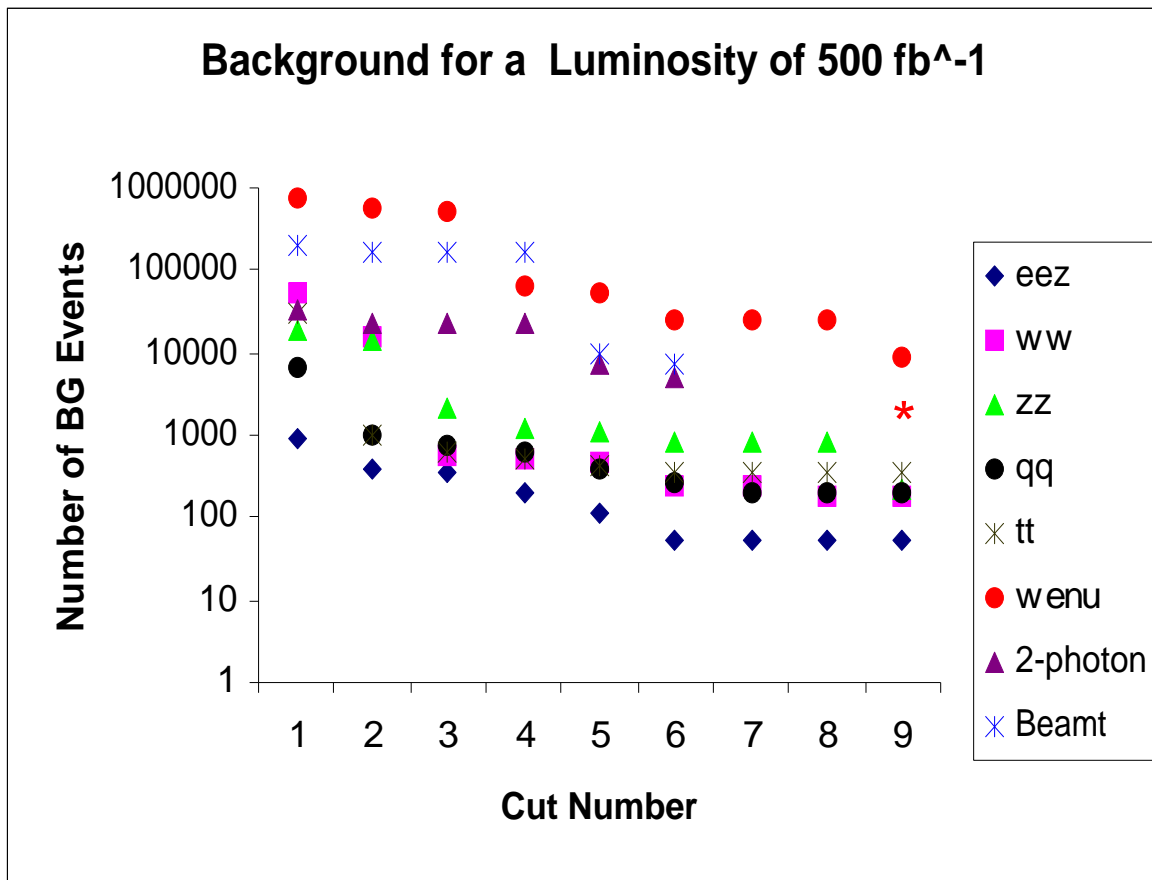
$\Delta M(\tilde{t}_1 - X_0)$

Selection: The Background Rejection

Background	% Left - End Presel	Number Gen. Selection	Num Events Left after End Sel. – For 500 fb ⁻¹	
YY	0.06%	5.5 Millions	0.	< 164.
zz	9%	0.03 M	35.	257.
qq, q≠t	0.09%	0.35 M	8.	160.
ww	1.45%	0.21 M	8.	145.
tt	1.36%	0.18 M	25.	38.
wev	25.70%	0.21 M	345	5044.
eez	0.06%	0.21 M	2	36.

The cut efficiency- And the number of background particles left normalized to 500fb⁻¹ are shown in the next figure for each BG channel separately.
Largest remaining Background :Wev

Selection: The Background



For a Luminosity of 500 fb⁻¹, the number of BG events left are reported after each of the 9 selection cuts

The c-tagging reduces the W_{ev} background to half its previous value, the red Star in the plot. It is the leading background

C-tagging-The Principle

A Vertex Identification followed by a Neural Network application
Developed by T. Khul for LEP.

- Vertex Identification:

As a maximum in track overlapping (product of probability density tubes defined using the track parameters)

3 cases:

Case 1) Only a primary Vertex

Case 2) 1 secondary vertex

Case 3) >1 secondary vertex

- Neural Network (NN):

data used: 255000 stops, $M_{\text{stop}}=120-220$; $D_m=5, 10, 20$ GeV
240000 W_{ev} , the most resilient background

C-tagging-Neural Network Input

- Vertex Case 1: NN Input variables

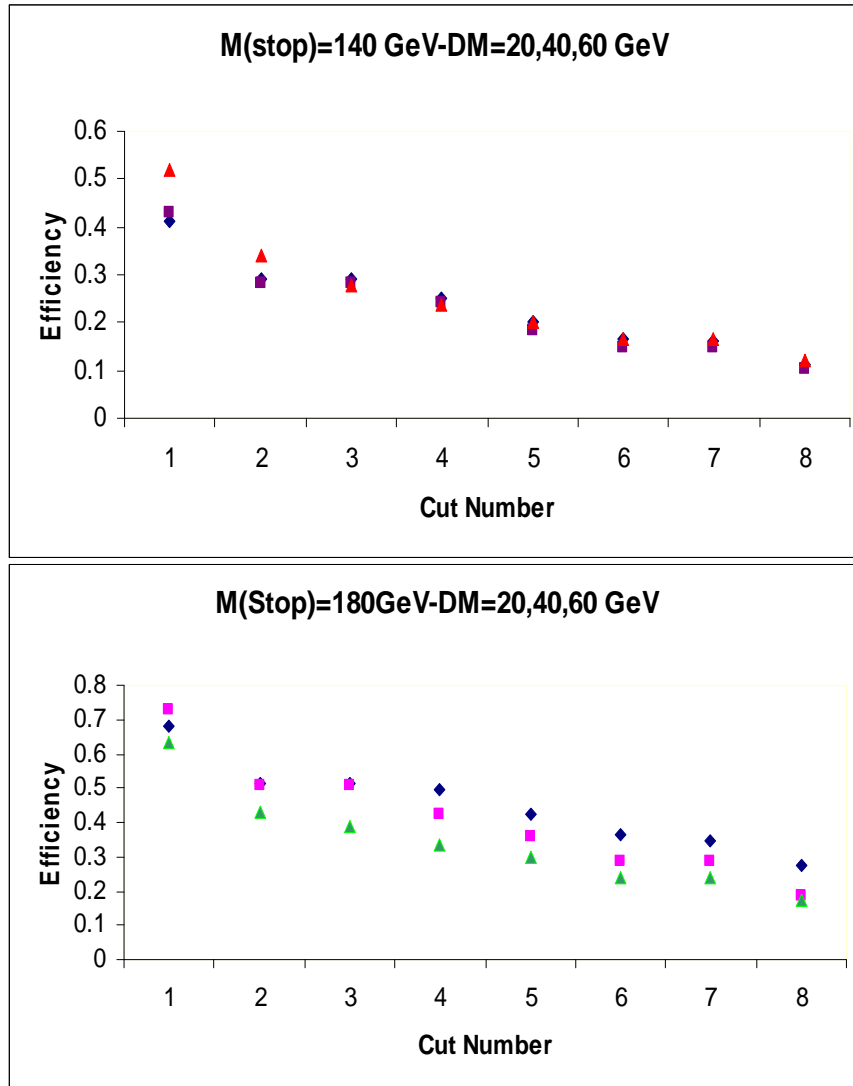
- *Impact parameter* significance (impact parameter/error) of the 2 most significant tracks in the r - Φ plane && their Impact parameters.
- The impact parameter significance & Impact parameters of the 2 tracks in z
- Their momenta
- The joint probability in r - Φ (tiny beam spot size in that plane) & z

- Vertex Case 2: NN Input variables (all of Case 1+below)

- *Decay Length* significance of the secondary vertex && Decay Length
- Momentum of all tracks associated to the secondary vertex && Multiplicity
- P_t corrected mass of secondary vertex (corrected for neutral hadrons & ν 's), the p_t of the decay products perpendicular to the flight direction (between primary && secondary Vertex) && joint probability in r - Φ and z

- Vertex Case 3: 2 secondary vertices, the tracks are assigned to the vertex closest to the primary vertex and the NN input variables are those of case 2

Selection: The Signal



The efficiency of the selection cuts is shown for the 140 GeV stop, upper plot and the 180 GeV stop, lower plot.

In each case it is represented for 3 neutralino masses, namely, $M(\tilde{t}-X_0)=20,40,60 \text{ GeV}$

The c-tagging allowed to relax the Previous cuts in

$\cos(\Phi_A\text{-coplanarity})$

$\text{Min}v^2_{\text{jets}}$

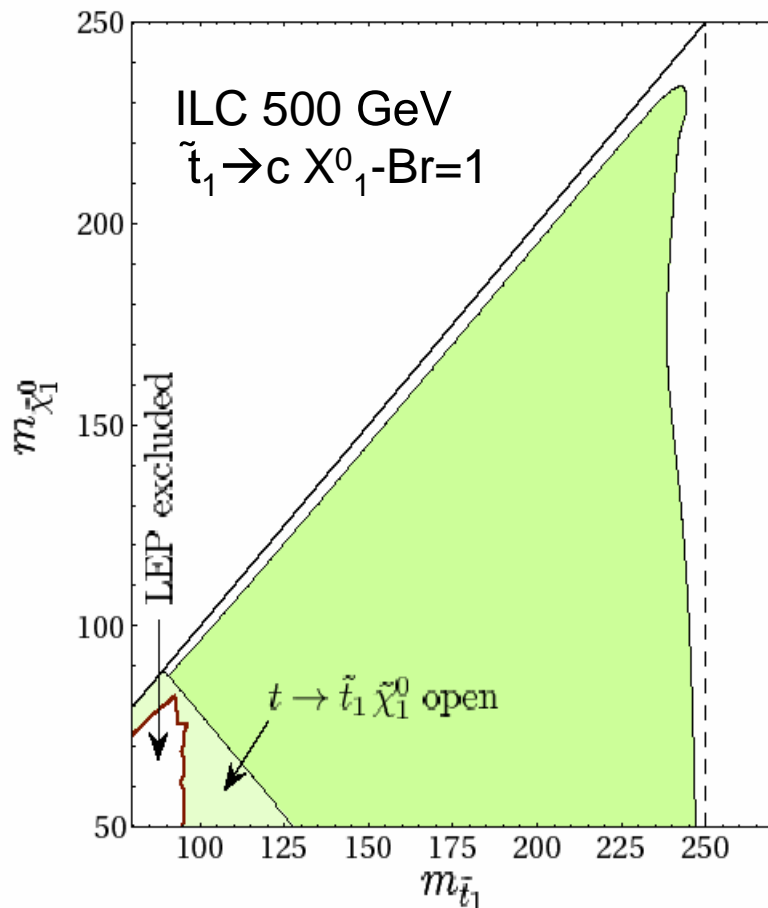
and allow to collect a slightly better To comparable Stop signal

Signal Efficiency

Δm (GeV)	$M\tilde{t}_1=120\text{GeV}$	$M\tilde{t}_1=140\text{GeV}$	$M\tilde{t}_1=180\text{GeV}$	$M\tilde{t}_1=220\text{GeV}$
80		10%	15%	19%
40		10%	20%	24%
20	17%	21%	28%	35%
10	19%	20%	19%	35%
5	2.5%	1.1%	0.3%	0.1%

- Highest Signal efficiencies are reached for $\Delta m=10\text{-}20$ GeV and exception made for $\Delta m=5$ GeV and the efficiency increases for higher $M\tilde{t}_1$.
- Overall Signal after selection cuts $\sim O(10^3)\text{-}O(10^4)$, remaining background $O(10^3)$ for 500fb^{-1}
- $\Delta m=5$ GeV were not included in the cuts optimization(besides c-tagging)

Stop Discovery reach



From Simulations:

- The ratio signal to background has been calculated, using signal efficiencies from the simulations for various $M_{\tilde{t}_1}$ and $M_{\tilde{\chi}_1^0}$ and the theoretical cross-section.
- For $(\text{Signal}/\sqrt{(\text{Signal} + \text{Bg})}) > 5$ we get the green region in the plot $M(\tilde{\chi}_1^0)$ - $M(\text{Stop})$.
- We did not yet study the region where the \tilde{t}_1 and $\tilde{\chi}_1^0$ masses are so light that they could come from the decay of the top (in light green-blue) and the 3-body decay.
- We can go to $\Delta m \sim \mathcal{O}(5 \text{ GeV})$ and cover the whole co-annihilation region

Stop Parameters Determination

Sample parameter point

Consistent with: Dark Matter; EW Baryogenesis; Higgs LEP bounds; Electric Dipole Moment

We use information from existing studies used when possible

$$MU3 = 0$$

$$MQ3 = 1.5 \text{ TeV}$$

$$At = -570. \text{ GeV}$$

$$\tan(\beta) = 6$$

$$M1 = 137.2 \text{ GeV}$$

$$M2 = 260. \text{ GeV}$$

$$|\mu| = 320 \text{ GeV}$$

$$\Phi_\mu = 0.2 \text{ [CP-violating phase of } \mu \text{]}$$

Which gives:

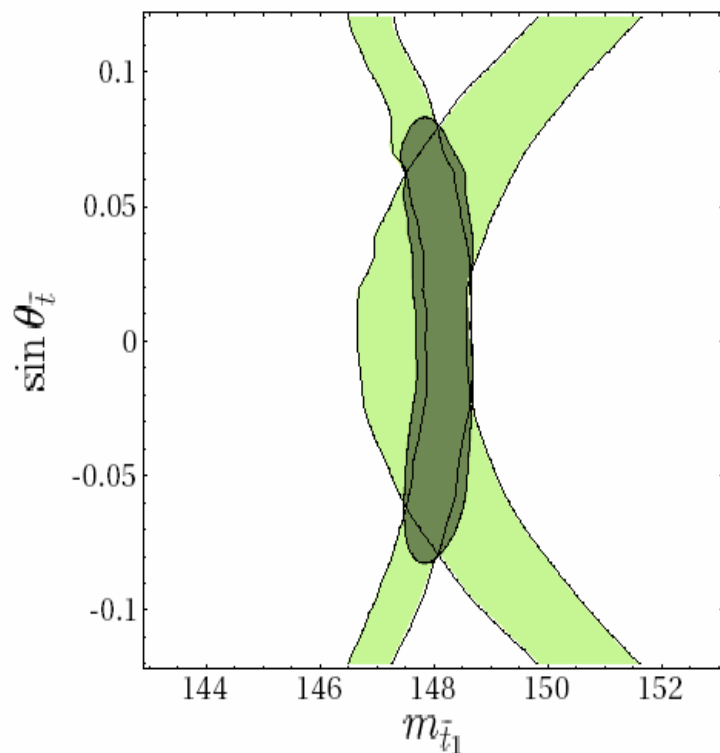
$$m_{X01} = 133.4 \text{ GeV}; m_{\text{stop}1} = 148.1, \sin\theta_t = 0.096$$

$$\Omega_{\text{DM}} h^2 = 0.115$$

$$\cos(\theta_{\tilde{t}}) = 0.985 \text{ [stop Mixing angle]}$$

In order to extract the stop parameters, we use the stop cross-section for $P(e^-)/P(e^+) = -80\%/+60\%$ and $P(e^-)/P(e^+) = +80\%/-60\%$ polarized beam, and 250fb⁻¹ luminosity for each polarization.

Stop Parameters Determination



The errors :

$\Delta m(x^0_1)=0.09$; Beam Polar. $\Delta p/p = 0.5\%$

Theoretical (Bg simul)= $\Delta(BG)/BG=0.3\%$

The Statistical Errors.

Uses $\sigma(e^+ e^- \rightarrow \tilde{t}_1 \tilde{t}_1^*)$ measured for 2 beam Polarization:

$P(e^-)/P(e^+) = -80\%/+60\%$; $+80\%/-60\%$

$L=250 \text{ fb}^{-1}$ each, and $dL/L=2 \cdot 10^{-4}$

Each of the two cross-section, with 2σ measurements, results in a band in the parameter plane of the stop mass and mixing angle

With these errors and the statistics we ran, the resulting 1σ bounds for the mass and mixing angle are

$$M(\text{stop}) = 148.1 \pm 0.4 \text{ GeV}$$

$$| \sin(\theta_{\text{stop}}) | < 0.07 ; | \cos(\theta_{\text{stop}}) | > 0.9975$$

Stop Parameters Determination-(Errors)

- Error on the $m_{\text{neu}(1)}$ mass: $d(m_{\text{neu}(1)}) = 0.09 \text{ GeV}$
LHC/ILC Study Group Working Report, eds. G.Weiglein {“Physics interplay of the LHC and the ILC,” hep-ph/0410364.
- Error on the beam polarization: $dP / P = 0.5\%$
G.~Moortgat-Pick , Beam Polarization at a future Linear Collider}, working group report in preparation.
- Background simulation (theoretical predictions): $d(BG) / BG = 0.3\%$
This estimate is based on the $(W e \nu)$ process as the largest background. While a complete NLO is still missing a recent result for the related process of W pair production is used.
- Luminosity: $d(L) / L = 2 \cdot 10^{-4}$ from Technical Design Report, Part IV, eds. T.~Behnke, S.~Bertolucci, R.D.~Heuer and R.~Settles, DESY-2001-011D.

Dark Matter Determination

- Mass Measurements:

- Light X^0_1 from selectron decay at ILC $\tilde{e} \rightarrow e X^0_1$,
Threshold scan of $m = f(\sqrt{s})$. $\rightarrow M_{X^0_1}, M_{X^0_2}, M_{X^0_3}, M_{X^+_1}$
- Other neutralino/chargino masses from ILC threshold scans
Mass Systematic errors estimated from LHC/ILC report 04

Remark: Heavy 1st/2nd generation of squarks, very little $\sigma \rightarrow$ difficult to measure neutralino Masses from squark cascades at LHC

- σ Measurements

For $P(e^-)/P(e^+) = -80\%/+60\%$; $+80\%/-60\%$ for $\sqrt{s} = 500, 600$ GeV

Assuming $dP/P = 0.5\%$ (Tesla Tech. report)

$\sigma(e^+ e^- \rightarrow X^+_1 X^-_1)$; $\sigma(e^+ e^- \rightarrow X^0_1 X^0_2)$; $\sigma(e^+ e^- \rightarrow X^0_2 X^0_2)$;

Analytical Estimate (S.Y. Choi et al), assuming systematic errors

And stat. errors, use a Chi2 to extract fundamental SUSY Parameters

- $M_W, M_Z, \sin\theta_W, \cos\theta_W$ from SM

$$M_1 = 137.2 \pm 0.2 \text{ GeV} \quad \left| \phi_\mu \right| = 0.2^{+0.8}_{-1.1}$$

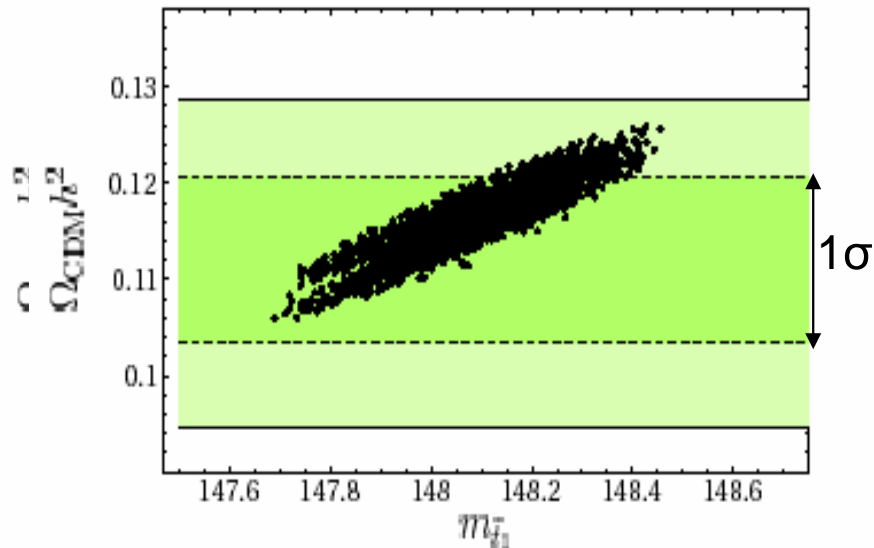
$$M_2 = 260.0^{+0.6}_{-0.9} \text{ GeV} \quad \tan\beta = 6^{+0.9}_{-3.2}$$

$$\mu = 320.0 \pm 3.3 \text{ GeV}$$

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Predictions For Dark Matter Density

D. Morissey's program was used to calculate Ω_{CDM}
(Balazs, Carena, Menon, Morissey, Wagner 04)



Using the stop parameters detailed above and combining estimated errors for Chargino and Neutralino, the collider measurements of the stop and Chargino/Neutralino parameters constrain the relic density at the 1- σ level (dark points) to:

$$0.107 < \Omega_{\text{CDM}} h^2 < 0.126$$

WMAP measurements (in green)

$$0.095 < \Omega_{\text{CDM}} h^2 < 0.129$$

So the overall precision is comparable to the direct WMAP determination. The uncertainty in the theoretical determination is dominated by the uncertainty in the stop mass, while the precision on the determination of the Neutralino, and Φ_μ and θ_{stop} are also important.

Conclusion

We have shown that with the linear collider we can cover the region of co-annihilation $\sim O(20-30\text{GeV})$ and even go down to $\sim O(5\text{GeV})$. The sensitivity to small mass differences is particularly important for the coannihilation mechanism

We can determine the parameters accurately enough to reach comparable precisions for the dark matter predictions than the direct WMAP measurements

Next to be done

- a) Further refinement of the analysis.
- b) Vary the parameters to analyze more dark matter cases.
- c) Optimization of the cuts for $\Delta m \sim 5 \text{ GeV}$ and below
- d) Scalar tops: possible benchmark reaction for vertex detector projects (e.g. Sopczak LCWS'04).

Starting International Collaboration involving Fermilab (USA), Lancaster (UK) within the LCFI (Linear Collider Flavor Identification) Collaboration and DESY (Germany).

Backup

Sample Parameter Points

- Calculation using a point giving a viable dark matter:
annihilations cross-sections: $\sigma(x_0, \text{stop})$, $\sigma(\text{stop}, \text{stop})$, $\sigma(X_0, X_0) \rightarrow$ relic density
- EW- Baryogenesis- $v(T_c) > T_c$ –out of equilibrium processes
stop light (bigger 1 loop correction)
Higgs Mass bound from LEP $m_{h_0} > 114.4$ GeV
- Important params at input M_A (heavy Higgs), μ , $\tan(\beta)$ + SM params+ stop params
- Electric Dipole Moment :
limit from experiment $|d_e| < 1.6 \cdot 10^{-27}$ cm
Heavy squarks for 1st & 2nd generation (consistency with dipole moment in Hg)
too heavy for hadron colliders (σ small at LHC & Tevatron)
 $M_{e_1} = 200$ GeV ($e_1 \rightarrow e X_0$) selectron mass energy scan & use($M_{\text{Inv}}(e)$)min & max)
 $M_{l1} = 2000$ GeV, $A_e = 4.5$ TeV $\exp(-i\pi/2)$

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